Assessment of Multi-Air Emissions: Case of Particulate Matter (Dust), SO_2, NO_x and CO_2 from Iron and Steel Industry of China

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Abstract: Industrial activities are generally energy and air emissions intensive, requiring bulky inputs of raw materials and fossil fuels and emitting huge waste gases including particulate matter (PM, or dust), sulphur dioxide (SO_2), nitrogen oxides (NO_x), carbon dioxide (CO_2), and other substances, which are severely damaging the environment. Many studies have been carried out on the quantification of the concentrations of these air emissions. Although there are studies published on the co-effect of multi-air emissions, a more fair and comprehensive method for assessing the environmental impact of multi-air emissions is still lacking, which can simultaneously consider the flow rate of waste gases, the availability of emitting sources and the concentrations of all emission substances. In this work, a Total Environmental Impact Score (TEIS) approach is proposed to assess the environmental impact of the main industrial processes of an integrated iron and steel site located in the northeast of China. Besides the concentration of each air emission substance, this TEIS approach also combines the flow rate of waste gases and the availability of emitting sources. It is shown that the processes in descending order by the values of TEIS are sintering, ironmaking, steelmaking, thermal power, steel rolling, and coking, with the values of 17.57, 16.68, 10.86, 10.43, 9.60 and 9.27, respectively. In addition, a sensitivity analysis was conducted, indicating that the TEIS order is almost the same with the variation of 10% in the permissible CO_2 concentration limit and the weight of each air emission substance. The effects of emitting source availability and waste gas flow rate on the TEIS cannot be neglected in the environmental impact assessment.

Keywords: environmental impact assessment; iron and steel industry; multi-air emissions; Total Environmental Impact Score (TEIS)

1 Introduction

Emissions of pollutants into the air will result in undesirable changes to the climate. According to the data of the United States Environmental Protection Agency (US EPA, 2016), principal air emissions include particulate matter (PM, or dust), sulphur dioxide (SO_2), nitrogen oxides (NO_x), carbon dioxide (CO_2), carbon monoxide (CO), lead and ozone. Industrial sectors are regarded as one of the most critical contributors of air emissions, and the environmental problems caused by them are attracting increasing attention in recent years (Propper et al., 2015).

Environmental impact assessment is a useful tool for conducting assessment and making decisions on industrial activities which are likely to have significant environmental effects (Jay et al., 2007). To assess the environmental impact of air emissions, Krittayakasem et al. (2011) listed the average annual emission inventory of CO_2, CO, NO_x, SO_2 and PM for the power industry of Thailand. Abu-Allaban and Abu-Qudais (2011) reported the emission concentration of PM, SO_2, NO_x and CO of a cement plant in Jordan. Sun et al. (2012) and Takeshita (2012) focused on the CO_2 emissions of Chinese iron and steel industry and global transportation industry, respectively. However, despite that many studies were conducted in various industrial sectors to assess different emitted substances separately, a unified index to measure the co-effect of these air emissions is essential. Generally, several types of substances will be emitted from an industry, and the real environmental impact or air quality is co-affected by all the air emissions. After all, lower CO_2 does not mean other emissions will be lower as well. Thus, air pollution index (API) and air quality index (AQI) have been applied to assess the co-effect of multi-air emissions (Pandey et al., 2014; Yadav et al., 2018). Although these two indices contributed a lot to the assessment of multi-air emissions, they only take the concentrations of emitted substances into account, without considering the flow rate of waste gases and the availability of emitting sources. Fan et al. (2018) summarised in a review paper that it remains an open and challenging question whether the available methodology is sufficient, as multi-air emissions are not always assessed comprehensively.

In order to fill the above research gap, this work aims to find an approach that can fairly and comprehensively assess the environmental impact of industrial multi-air emissions. The air emissions of the iron and steel industry is a matter of urgent concern and selected as a case study, because of its vast materials and energy consumption (Sun et al., 2018a), numerous emitting sources (Li et al., 2018), multifarious emission substances (Yang et al., 2018), and high emission intensities (Du and Lin, 2018).

2 Literature Review

As a resource-based, energy-consuming, and emission-intensive industry, iron and steel sites generally expel multiple types of air emissions, including PM, SO_2, NO_x, CO_2, CO, volatile organic compound and dioxin (Abdul-Wahab, et al., 2018; Wu et al., 2015), which significantly impact the regional and global air quality.

CO_2 emission from the iron and steel industry has been brought into sharp focus by global warming. Siitonen et al. (2010) analysed the variables affecting CO_2 emissions from the iron and steel industry. Many other researchers assessed the trend of CO_2 emission, especially for the energy-related CO_2 emissions (Peng et al., 2018), for the iron and steel industry of China (An et al., 2018; Wang et al., 2017; Xu et al., 2016), Japan (Kuramochi, 2016), India (Das and Kandpal, 1998) and Thailand (Sodsai and Rachdawong, 2012). Taking China as an example, annual CO_2 emissions from the Chinese iron and steel industry are approximately 1.6 billion tonnes (Zhang et al., 2018). Van Ruijven et al. (2016) statistically reported that CO_2 emissions from global iron and steel industry are projected to peak (2.7-2.9 tonne CO_2 per tonne of steel) in the next decades followed by a decrease to around 1.2-1.4 tonne of CO_2 per tonne of steel in 2050. It can be seen that CO_2 emissions from the iron and steel industry is a big concern. However, few studies are focused on the environmental impact of CO_2 compared with other types of air emissions.

Due to the spate of haze, particular attention has been paid to PM emission (Peters et al., 2018). Research on the environmental impact assessment of PM is mainly focused on the emission concentration of PM. Contrary to the statistical method widely used in CO_2 emission assessment, PM emission assessment is usually based on monitoring data. Zhao et al. (2017) assessed the PM emission from the sintering process of an integrated steelworks located in northern China, with a level of 0.121 kg per tonne of sinter ore. Li et al. (2019) analysed the PM emission characteristics of a 3200 m^3 blast furnace in an ironmaking process, with the levels being 39.3 per tonne of hot metal for the bunker system, 54.0 per tonne for the cast house and 1.5 g per tonne for the pulverised coal feeding system. Moreover, Sylvestre et al. (2017) quantified the chemical components of PM from steelmaking activities of a French metallurgical complex. Sun et al. (2016) summarised the emission factors of primary PM in iron- and steelmaking processes. Taiwo (2014) conducted a site sampling in South Wales, the UK to investigate the PM emission factors. The recently published papers showed that the assessment of PM emitted from the iron and steel industry is a currently hot topic, but the details of the physicochemical characteristics are still not clear, and the co-assessment with other pollutants remains to be studied.

Though there are many studies on desulphurization and denitrification, only a few studies were reported on the accounting and assessment of SO_2 and NO_x emissions. Ma et al. (2012) assessed the SO_2 emission potential by developing a material flow analysis model of the iron and steel industry. They expected that the SO_2 emission factors of coking, sintering, pelletising, ironmaking, basic oxygen steelmaking, and electric arc steelmaking processes are 0.326, 1.374, 0.395, 0.837, 0.039 and 0.026 kg per tonne of key product, respectively. Nurrohim and Sakugawa (2004) and Ohara et al. (2007) developed an SO_2 and NO_x emission inventory for the iron and steel industry.

From the literature survey above, the emission intensity of a single type of emission substance is widely analysed for environmental impact assessment, but in reality the air quality is co-affected by the multi-air emissions. With the development of environmental impact assessment, multi-air emissions have been becoming a hot topic. Wu et al. (2015) predicted the future emissions of SO_2, NO_x, PM, VOCs, and PCDD/Fs. Wang et al. (2016) reported a comprehensive emission inventory including PCDD/Fs, heavy metals, SO_2, and PM. Abdul-Wahab et al. (2018) evaluated the ground-level concentrations of SO_2, NO_x, CO, and PM emitted from a steel melting plant. However, it is not sufficient to assess the environmental impact of multi-air emissions only by the concentration data. In order to assess the co-effect of multi-air emissions, air pollution index (API) was defined as the ratio of the emission substance concentration to the national standard and used to assess the environmental impact of a coal mining area (Pandey et al., 2014). Recently, this index was updated to air quality index (AQI) and used for assessing the air emissions of two coalfields (Yadav et al., 2018). Despite these research progresses, the emitting sources operate intermittently in many applications, and the flow rate of waste gases varies. These factors have not been considered in existing studies.

Thus, a comprehensive assessment of multi-air emissions simultaneously considering the concentrations of air emissions, the flow rate of waste gases, and the availability of emitting sources remains to be studied. In addition, the lack of field data makes it more challenging for the comprehensive assessment to be implemented (Fan et al., 2018). Moreover, controlling individual emission without considering synergistic effects could lead to divided and costly technology pathways (Wu et al., 2018). Therefore, it is of significance to find a rational index that can be used to assess the comprehensive environmental impact of multi-air emissions fairly.

No research has yet been done to consider the flow rate of waste gases and the availability of emitting sources in environmental impact assessment of multi-air emissions. To fill the gap, a total environmental impact score (TEIS) approach introduced from wastewater discharge assessment (Sun et al., 2019) is proposed in this work to assess the co-effect of multi-air emissions. The contribution of the proposed approach is that the flow rate of waste gases and the availability of emitting sources are considered, besides the emission concentration. An integration of these factors is expected to be used for the rational assessment of multi-air emissions. Also, simultaneous monitoring of multi-air emissions, including PM, SO_2, NO_x and CO_2, from an integrated iron and steel site was conducted in reality, differing from previous studies which use a referenced emission factor list provided by environmental agencies. Based on these monitoring data, an assessment of multi-air emissions of a real iron and steel site and the corresponding sensitivity analysis were conducted.

3 Methodology

To comprehensively and fairly assess the environmental impact of multi-air emissions, the candidate index should be satisfied with the following features:

• Rationality, which means that the index can truly reflect the environmental impact of multi-air emissions.

• Objectivity, which requires that the index and the relevant parameters can be measured or calculated quantitatively.

• Integrality, which requires that the index covers all the factors with no information overlap.

• Operability, which means that the index and the relevant parameters can be obtained easily.

In this work, the total environmental impact score (TEIS) of an industrial process is defined to assess the environmental impact of multi-air emissions. Compared with the existing indices (API and AQI) defined as (Pandey et al., 2014; Yadav et al., 2018)

$$API\ or\ AQI = \frac{1}{J}\sum_{j=1}^{J}\left(\frac{c_j}{c_{0j}}\right), \quad 1)$$

the TEIS simultaneously considers the concentration of each emission substance, the flow rate of the waste gases, and the availability of the emitting sources, with the expression as

$$TEIS = \sum_{i=1}^{I}\sum_{j=1}^{J}\left(\omega_j \cdot r_i \cdot \frac{c_{i,j}}{c_{0i,j}} \cdot \frac{q_i}{q_{0i}}\right) \quad 2)$$

where i and j represent the index of emitting sources and emission substances, respectively; ω denotes the weight of corresponding emission substance; c and c_0 are the actual and permissible emission concentration, respectively [mg/m^3] or [%]; q and q_0 are the actual and referenced flow rate of waste gases, respectively [m^3/h]; I and J are the numbers of emitting sources and emission substances of the investigated industrial process, respectively; and r is the availability of an emitting source [%], which equals to the proportion of time when an emitting source is functioning within a year.

Comparing Eqs. (1) and (2), it can be found that:

- The term (c/c_0) in TEIS and API/AQI is the same, which measures the environmental impact of an emission substance by taking the ratio of its actual emission concentration to the permissible emission concentration. The permissible emission concentrations are usually set by the governments. If there is no official standard on permissible emission concentration, the average concentration of all the emitting sources can be used as an alternative. The actual concentration of gaseous emissions can be easily measured by using gas concentration sensors. By contrast, as a solid phase air emission, the concentration of PM is usually determined by a gravimetric method and calculated by (Wang et al., 2018)

$$c_{\mathrm{PM}} = \frac{m_2 - m_1}{q^*} \tag{3)}$$

where m_1 and m_2 are the mass of PM-collecting filter cylinder before and after sampling, respectively [mg]; q^* is the volume of sampled waste gas [m^3].

• The term (q/q_0) in TEIS is to consider the flow rate of waste gas besides the emission concentration. The product of concentration and flow rate is the mass of the emission substance, which reflects the total quantity of the air emission. The TEIS that considers the flow rate of waste gases is more reasonable and fairer for assessing the environmental impact. The actual flow rate can be monitored by using a flow sensor, whilst the referenced flow rate of waste gases is set by the government. If it has not been set by the government, an artificially set value according to the characteristics of the investigated emitting source can be used.

• The term r in TEIS is the availability of an emitting source. It is clear that the availability of emitting sources contributes greatly to the environmental impact since some emitting sources operate intermittently. The availability is defined as the ratio of the annual operating time (in hour) of the emitting source to the total hours of a year and can be calculated by

$$r = \frac{annual\ operating\ hours}{total\ hours\ in\ a\ year\ (8760\ \mathrm{h})} \tag{4}$$

• The term ω is considered in TEIS, because the environmental impact of one emission substance may differ from others' even with the same emission quantity. Therefore, the weight of each emission substance should be considered in TEIS. However, it is difficult to decide the weight values in Eq. (2) exactly. Before a sensible method is invented to determine the weight set, it is acceptable to consider that different types of emissions have equivalent effect, as assumed in API and AQI. Thus, in this work, the effect of various emission substances with the same amount is regarded as the same. That is, the weights for all air emissions are all equal to 1 as a first attempt. To develop more reasonable weights to reflect the effect of each substance may be a research topic for the future.

• The term $(1/J)$ is removed from TEIS, compared to API/AQI presented in Eq. (1). If the emitting sources produce the same set of emissions, the API or AQI performs well in evaluating the emitting sources' environmental impact. However, if the emitting sources produce different sets of emissions, conflicting performance results may be observed. For example, three substances A, B and C are emitted from source #1, and four substances, A, B, C and D, are emitted from source #2. For both source #1 and #2, it is assumed that the concentration of each type of emission is 20 mg/m^3, with the same individual permissible limit of 50 mg/m^3. Given these, the AQIs of source #1 and #2 are both 0.4 according to Eq. (1), which means they are equally harmful to the air quality. Obviously, this is unreasonable. By contrast, it can be seen from Eq. (2) that for the TEIS approach proposed, the TEIS is 1.2 for source #1 while it is 1.6 for source #2, which is more reasonable. This is because in TEIS, the environmental impact of each substance is accumulated but not being divided by the number of the substances, which is different from the existing average-based method (API and AQI).

4 Experimental Design

4.1 Site Description

The area studied is an integrated iron and steel site located in the northeast of China. The site is one of the largest steel producers in China, with an annual production capacity of approximately 21 Mt of crude steel. It is a complex process mixture, mainly consisting of coking, sintering, ironmaking, steelmaking, steel rolling, and thermal power processes. A set of emitting points are listed in Table 1.

Table 1 Location and emission substances of emitting sources

process	emitting source	abbreviation of the emitting source	PM	SO_2	NO_x	CO_2
coking	coal charging car	CCC	Y	Y	Y	Y
	coke pusher and guide car	CPG	Y	Y	N	N
	coke oven stack	COS	Y	Y	Y	Y
	coke screening station	CSS	Y	N	N	N
	coke conveyor	CCV	Y	N	N	N
	coke dry quenching tower	CDQ	Y	Y	Y	Y
sintering	flux conveyor	SFC	Y	N	N	N
	proportioning room	SPR	Y	N	N	N
	sintering machine	SSM	Y	Y	Y	Y
	annular cooler	SAC	Y	Y	Y	Y
	screening room	SSR	Y	N	N	N
ironmaking	bunker	IBK	Y	N	N	N
	cast house	ICH	Y	N	N	N
	hot blast stove stack	IBS	Y	Y	Y	Y
	railway tanker	IRT	Y	N	N	N
steelmaking	hot metal preparation station	MHM	Y	Y	Y	Y
	bulk material room	MBM	Y	N	N	N
	converter	MCT	Y	N	Y	Y
	secondary refining	MSR	Y	N	Y	Y
steel rolling	reheating furnace stack	RRF	Y	Y	Y	Y
	finishing mill	RFM	Y	N	N	N
thermal power	boiler stack	TPB	Y	Y	Y	Y

Note: Y – the emitting source emits the substance; N – the emitting source does not emit the substance.

4.2 Sampling and Monitoring

In the case study, the air emissions considered include CO_2, SO_2, NO_x, and PM. Among them, the first three, CO_2, SO_2 and NO_x, are gaseous emissions which can be mixed uniformly, and thus, can be monitored accurately. The monitoring of SO_2, NO_x and CO_2 in waste gases was conducted by using corresponding built-in sensors of an Automatic Stack Dust/Gas Tester 3012H (Laoshan Applied Technology Research Institute, China). As a solid particulate, the PM in the waste gases is relatively turbulent and should be repeatedly monitored also by using the Automatic Stack Dust/Gas Tester 3012H with the components of the waste gases as input parameters. For each emitting source, the PM was sampled three times with 1 hour for each sampling. The final concentration of the PM is calculated by taking the average of the three monitored concentrations for each emitting source. Samples of PM were collected with the same flow rate of waste gases under normal operating conditions. The flow rate of waste gases was also measured by the Tester 3012H. In order to achieve the isokinetic sampling conditions, the tester automatically adjusts its sampling rate according to the real-time measured values of temperature, flow rate and humidity ratio of the waste gases. In addition, a superfine glass fibre filter cylinder was used for the PM sampling because of its high trapping efficiency and high-temperature resistance. Filter cylinders were weighed both before and after the sampling, then the concentration of PM can be calculated according to Eq. (3).

5 Results and Discussion

5.1 Field-Measured Data

Fig. 1 illustrates the measured and permissible concentration of PM, SO_2, NO_x and CO_2 emitted from the 22 emission sources. The permissible limits of emitting PM, SO_2, and NO_x were selected from China National Standards, including GB 16171-2012 for coking process (MEE and AQSIQ, 2012a), GB 28662-2012 for sintering process (MEE and AQSIQ, 2012b), GB 28663-2012 for ironmaking process (MEE and AQSIQ, 2012c), GB 28664-2012 for steelmaking process (MEE and AQSIQ, 2012d), GB 28665-2012 for steel rolling process (MEE and AQSIQ, 2012e), and GB 13271-2014 for boiler in the thermal power process (MEE and AQSIQ, 2014).

It can be found from Fig. 1 that different permissible limits are set for different emitting sources and air emissions. Most of the emitting sources meet the permissible limit of PM except for SFC, SSR, IBK, MHM, and MBM. CPG contributes most to the PM emission concentration with the level of 38.12 mg/m^3, followed by SSM and MBM with the levels of 36.00 and 35.23 mg/m^3, respectively. TPB in thermal power process has the lowest PM concentration of 6.7 mg/m^3.

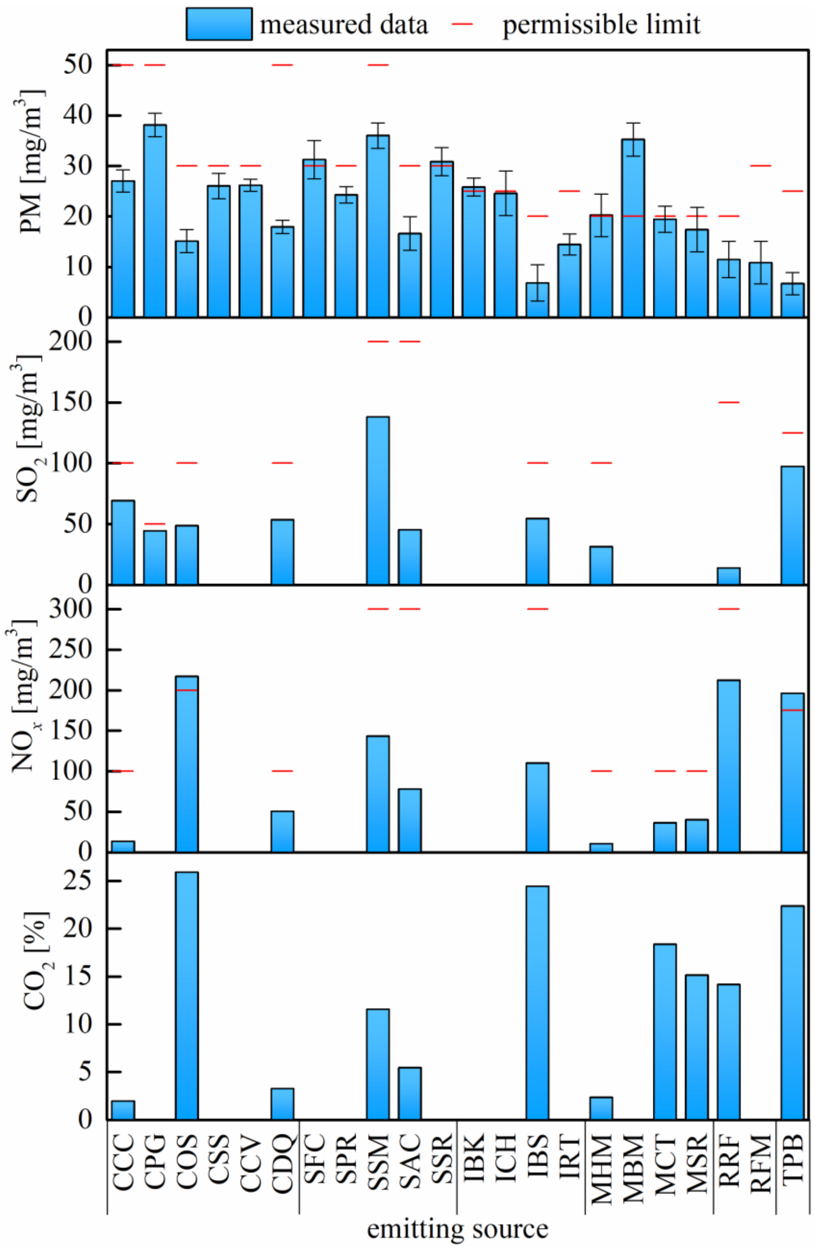

Fig.1 Measured concentrations and permissible limits

Contrary to the solid phase PM emissions, gaseous emissions including SO_2, NO_x and CO_2 are generated mainly from the combustion process. Thus, these three emissions are not emitted from mechanical processes, such as CSS, CCV, SFC, SPR, SSR, IBK, ICH, IRT, MBM, and RFM. For SO_2, all the emitting sources meet the permissible limits in the investigated iron and steel site. SSM ranks the first in the concentration of SO_2 with the level of 138.26 mg/m^3, followed by TPB of 97.49 mg/m^3. For NO_x, COS, RRF and TPB occupy the

Top 3 with the concentration levels of 217.28, 212.37 and 196.24 mg/m^3, respectively. For CO_2, the average value of 13.2% serves as a referenced limit in this study. The primary emitting sources are COS, IBS, and TPB, with the concentration levels being 25.94%, 24.47%, and 22.39%, respectively.

Another interesting finding is that the dominant emitting sources of the gaseous emissions usually have a relatively low PM concentration. For instance, TPB ranks 2nd, 3rd and 3rd, respectively, in the concentration of SO_2, NO_x and CO_2, while has the lowest PM concentration. This is because the fuels consumed in TPB are just by-product gases, including blast furnace gas, coke oven gas and Linz-Donawitz gas (Sun et al., 2018b). The combustion products are mainly composed of these gaseous air emissions according to the corresponding chemical reactions. However, the generated PM is mainly fine particles with the aerodynamic diameter of less than 2.5 μm.

Environmental impact of air emissions depends not only on the concentrations of emission substances but also on the waste gas emissions. Fig. 2 depicts the proportions of waste gas emission from the 22 emitting sources. Ironmaking process is the biggest waste gas emitter, accounting for 29.31% of the total waste gas emissions of the whole site, followed by sintering, steelmaking, coking, steel rolling, and thermal power process with the proportions of 26.23%, 13.64%, 12.63%, 12.11%, and 6.09%, respectively.

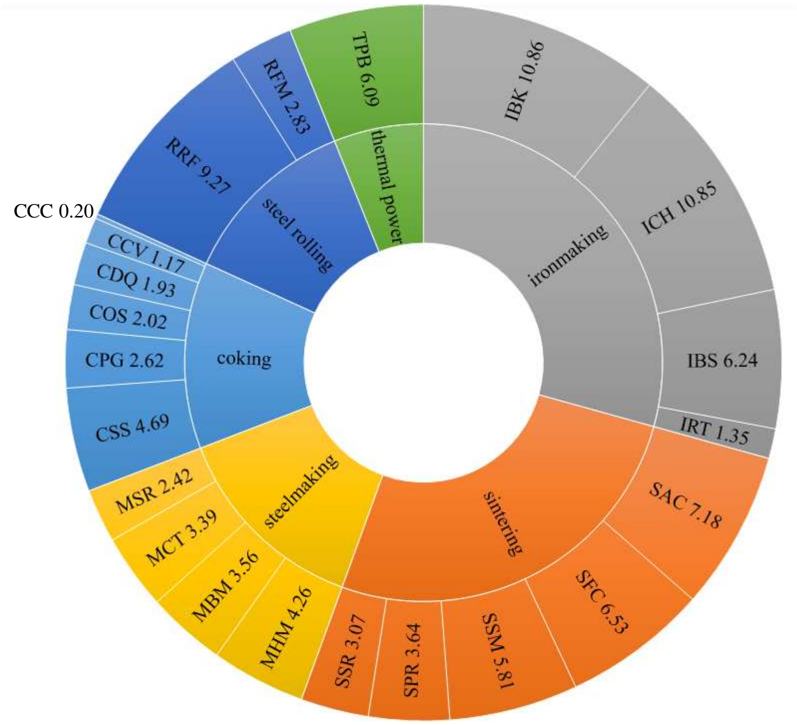

Fig. 2 Share of waste gas emissions [%]

The availability of an emitting source is another parameter that affects the environmental impact of the emitting source. The statistics of annual availabilities of all the 22 emitting sources are shown in Fig. 3. It can be seen that only emitting sources in the coking process have 100% availability because of their particular characteristics, while most emitting sources need maintenance or temporarily out of service.

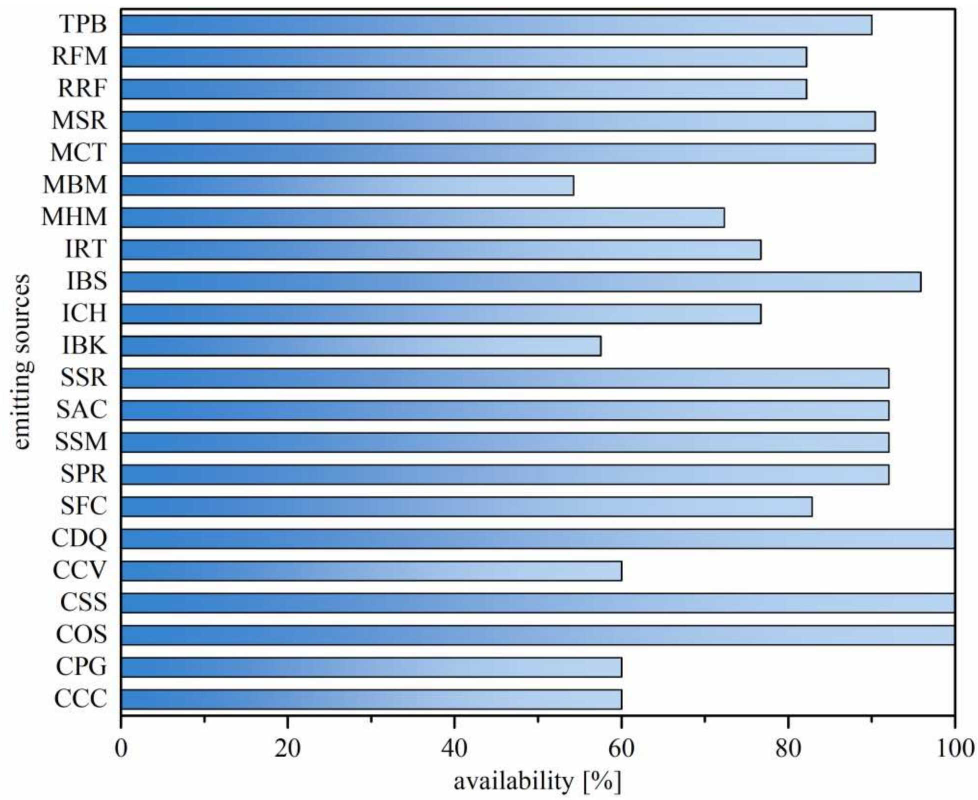

Fig. 3 Availabilities of emitting sources

5.2 Environmental Impact Assessment

As the referenced flow rate of waste gases for Chinese iron and steel industry has not been set by the government so far, it could only be set artificially in this case study. For the investigated iron and steel site, the actual flow rates of all the emitting sources vary from 0.09 to 5.35 million m^3/h. For simplicity, a value of 1 million m^3/h was selected as the referenced flow rate in this work. In addition, the CO_2 emission potential is widely evaluated using the mass reduction of emissions, rather than setting a limit of emission concentration. Therefore, in this work, the average concentration of all the CO_2 emitting sources is employed, as a trial, since there is not a permissible emission concentration for CO_2 set by the government.

Fig. 4 presents the TEIS of the main processes of the site. The TEIS relationship of all emitting sources is listed in descending order as: sintering, ironmaking, steelmaking, thermal power, steel rolling, and coking. Sintering process has the highest TEIS of 17.57, within which PM contributes the most, followed by CO_2, SO_2 and NO_x. The TEISs of coking and ironmaking processes are 9.27 and 16.68, respectively, with the same trend of contributors. The TEIS of the steelmaking process is 10.86. Its primary contributors are also PM and CO_2, but the smallest one is SO_2. This is because that only MHM contributes to the SO_2 emission of the steelmaking process, while the following production units are sulphur-free. The TEISs of steel rolling and thermal power processes are 9.60 and 10.43, respectively. CO_2 and NO_x are the main contributors to the TEIS of the two processes because of the combustion of by-product gases. PM contributes the least to thermal power process, but contributes more to the TEIS than SO_2 in steel rolling process. Consequently, the air emissions from sintering and ironmaking processes should be significantly focused on. In addition, more attention should be paid on steel rolling and thermal power processes, even if they look cleaner than steelmaking and coking processes.

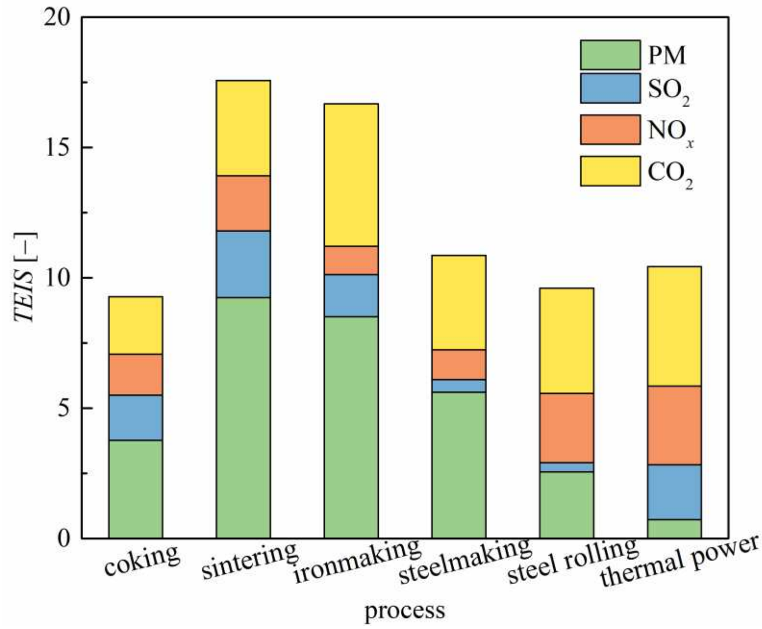

Fig. 4 TEIS assessment of main processes

Fig. 5 presents the contribution of different emitting sources of all processes. COS is a leading emitter in the coking process, with the proportion of 43.42%, because of its highest availability and the concentration of NO_x and CO_2. CSS, the second largest emitting source, with a moderate PM concentration and no other air emissions, accounts for 21.61% of the

TEIS of the coking process because of its largest flow rate of waste gas, which constitutes 37.13% of the total waste gas emissions of the coking process. SSM and SAC totally account for 68.46% TEIS of the sintering process because of their high emission concentrations, waste gas flow rates and emitting source availabilities. IBS takes the first place in the ironmaking process, with the proportion of 54.99%, because it is the only emitting source that has all the four air emission substances. In the steelmaking process, MCT and MSR rank the first and the second with the proportions of 37.97% and 24.05%, respectively, due to their high availabilities and CO_2 emission concentrations from the smelting process. RRF presents an overwhelming proportion of 95.69% in the steel rolling process, while there is only TPB in the thermal power process.

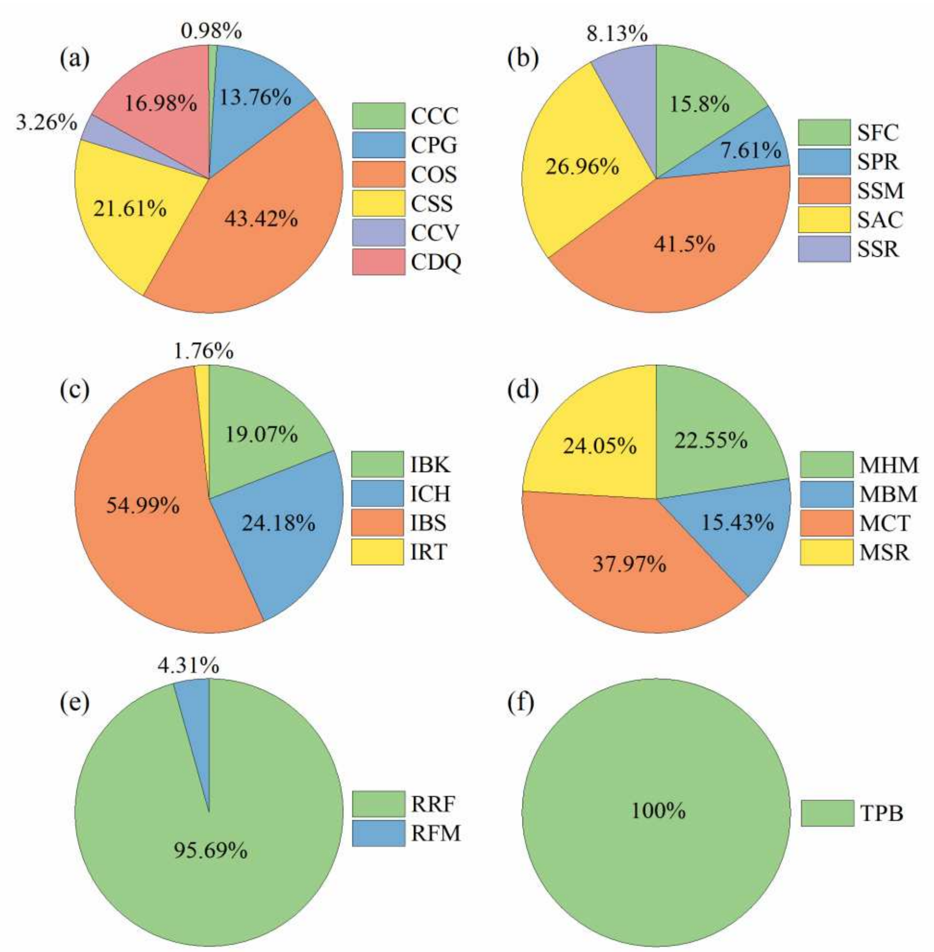

Fig. 5 Contribution of each emitting point to the TEIS of each process: (a) coking, (b) sintering, (c) ironmaking, (d) steelmaking, (e) steel rolling, and (f) thermal power.

Fig. 6 compares the results of the TEIS approach and an adapted average-based method with and without NO_x as an air emission substance. The adapted average-based method is defined as the TEIS divided by the number of air emission substances. It is selected as the reference method to demonstrate why the proposed TEIS is not defined to be divided by the number of air emission substances. It can be found that the results of steel rolling and thermal power processes based on the adapted average-based assessment with NO_x as a substance are higher than those without NO_x. However, for coking, sintering, ironmaking and steelmaking processes, conflicting results occur in the adapted average-based assessment. Taking the sintering process as an example, when NO_x is not considered, the average-based TEIS of PM, SO_2 and CO_2 is 5.15, which is the sum of the TEIS of PM, SO_2 and CO_2 divided by 3. However, if NO_x is considered, the average-based TEIS becomes the sum of the TEIS of PM, SO_2, NO_x and CO_2 divided by 4, resulting in a reduction of the TEIS of the process to 4.39, which is not reasonable. By contrast, since the total TEIS is the sum of every single substance, it is obvious that the more the substances are, the higher the TEIS is. Thus, TEIS of each process with NO_x considered is higher than that without NO_x. Therefore, the TEIS approach is more feasible in assessing the environmental impact for different sets of air emission substances.

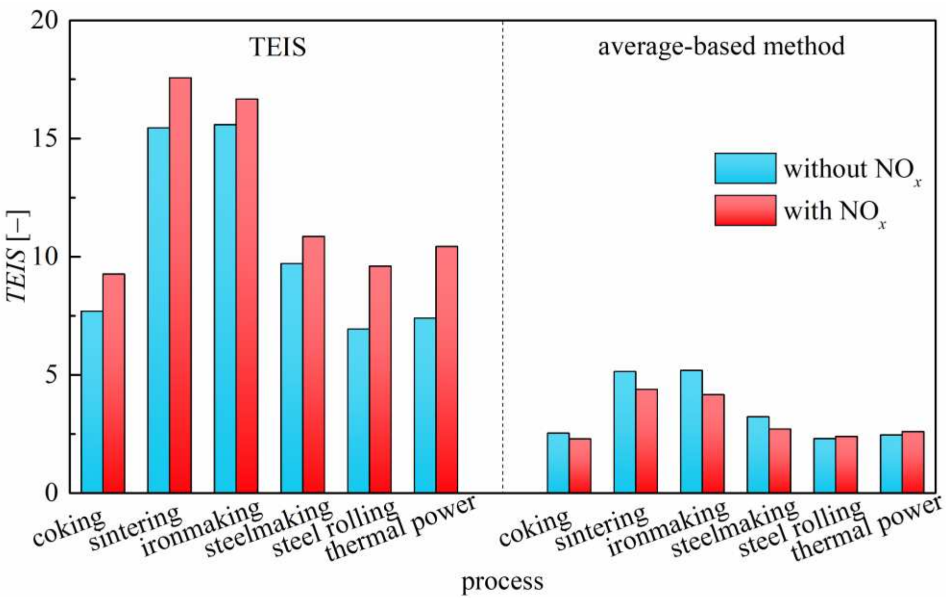

Fig. 6 Comparison of TEIS with the average-based assessment method

Fig. 7 displays the comparison of TEIS with and without considering the availability of emitting sources and waste gas flow rate. It can be seen that the TEIS of coking, sintering, ironmaking, steelmaking, steel rolling, and thermal power process will increase by 12.00%, 10.54%, 24.31%, 28.22%, 21.67%, and 11.11%, respectively, if the availabilities were assumed as 100% without considering their real availabilities. If so, the real environmental impact will be overestimated. However, if the flow rate of waste gases is not taken into account, the TEISs of these processes will reduce by 3.03%, 63.34%, 71.38%, 37.58%, 75.96%, and 66.65%, respectively. Accordingly, the environmental impact will be underestimated severely. In addition, compared with TEIS, if a method considers neither availability nor waste gas flow rate, the effect of not considering emitting source availability and not considering waste gas flow rate will be accumulated.

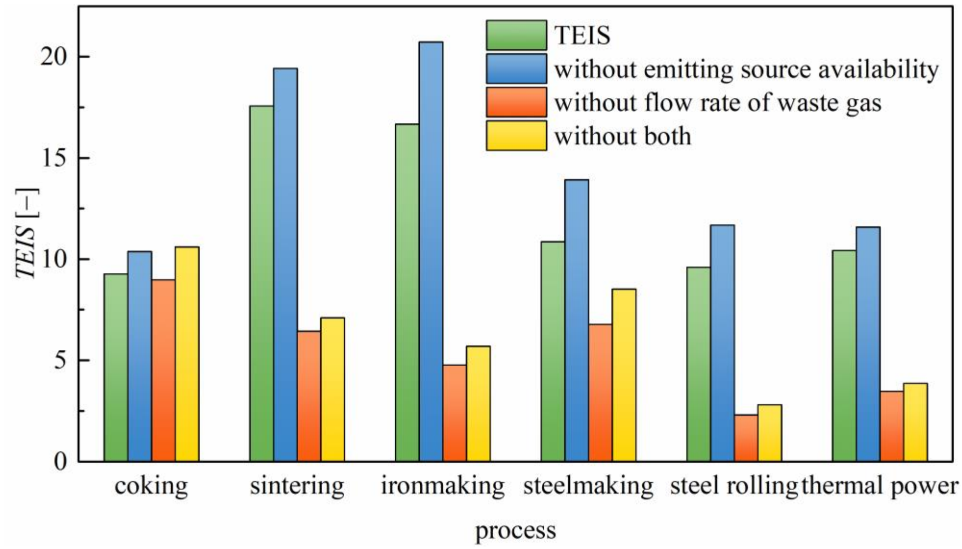

Fig. 7 Comparison of TEIS with and without constraints

5.3 Sensitivity Analysis

The permissible limit of CO_2 was selected as the average value of all emitting sources, and the weight of each air emission substance was set as 1 in this work. Changes in these parameters might lead to different results. Therefore, a sensitivity analysis was conducted by varying the parameters.

Fig. 8 shows the results of the sensitivity analysis with the permissible limit of CO_2 emission concentration increased and decreased by 10%. It is found that the TEISs of coking, sintering, ironmaking, steelmaking, steel rolling and thermal power processes will reduce by 2.16%, 1.89%, 2.98%, 3.03%, 3.82% and 3.99%, respectively if the increment in the permissible limit of CO_2 concentration is 10%. By contrast, they will increase by 2.64%, 2.31%, 3.64%, 3.70%, 4.67% and 4.88%, respectively if the permissible limit declines by 10%. No matter the permissible limit of CO_2 increases or decreases, the order of the TEIS for the processes is still the same, being sintering, ironmaking, steelmaking, thermal power, steel rolling, and coking (in descending order). No permissible limit for CO_2 emission issued by the government is a challenge and limitation of this work. In this case study, the average CO_2 concentration of all CO_2 emitting sources was chosen as the criterion. It is not necessarily the most reasonable solution, but for emission substances currently without a governmental standard, it provides an option to make things work.

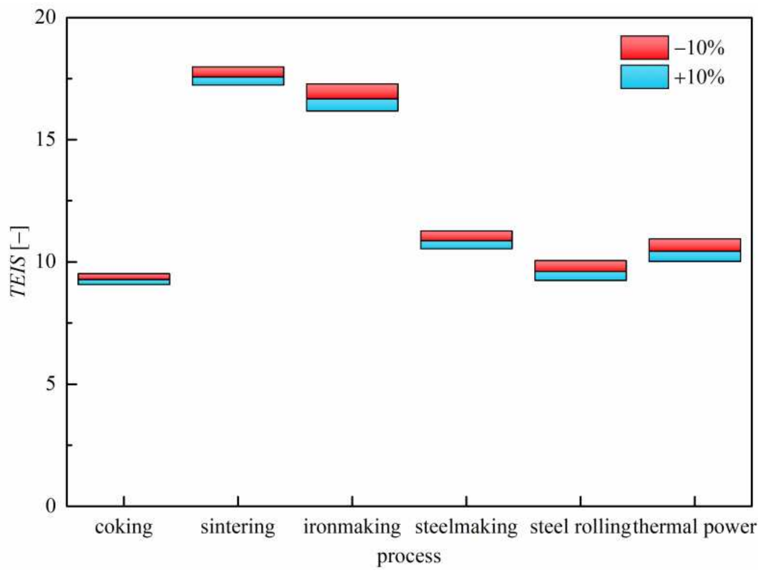

Fig. 8 Sensitivity analysis of permissible CO_2 emission limit

Fig. 9 examines the sensitivity of the weights of PM, SO_2, NO_x and CO_2. If the weight of PM varies by 10%, the TEISs of coking, sintering, ironmaking, steelmaking, steel rolling and thermal power process will vary by 4.07%, 5.26%, 5.10%, 5.17%, 2.67% and 0.69%, respectively. Likewise, they will have a change of 1.86%, 1.46%, 0.97%, 0.44%, 0.36% and 2.02%, respectively, with a variation of 10% in the weight of SO_2; 1.70%, 1.20%, 0.65%, 1.06%, 2.77% and 2.90%, respectively, with the change of 10% in the weight of NO_x; and 2.38%, 2.08%, 3.28%, 3.33%, 4.20% and 4.39%, respectively, as the weight of CO_2 changes by 10%. In most cases, with the exception of PM, the TEIS has the same descending sequence as follows: sintering, ironmaking, steelmaking, thermal power, steel rolling, and coking. However, the case where the weight of PM reduces 10% turns the TEISs into a new descending sequence: sintering, ironmaking, thermal power, steelmaking, steel rolling, and coking. From this point of view, the assumption that the weights for all air emissions were set as 1 needs to be further improved in future studies. In spite of this, as the first trial of TEIS in the assessment of multi-air emissions, the results of sensitivity analysis basically met the expectations except the case where the weight of PM changes. More reasonable weight sets reflecting the effect of each substance may be a future research domain.

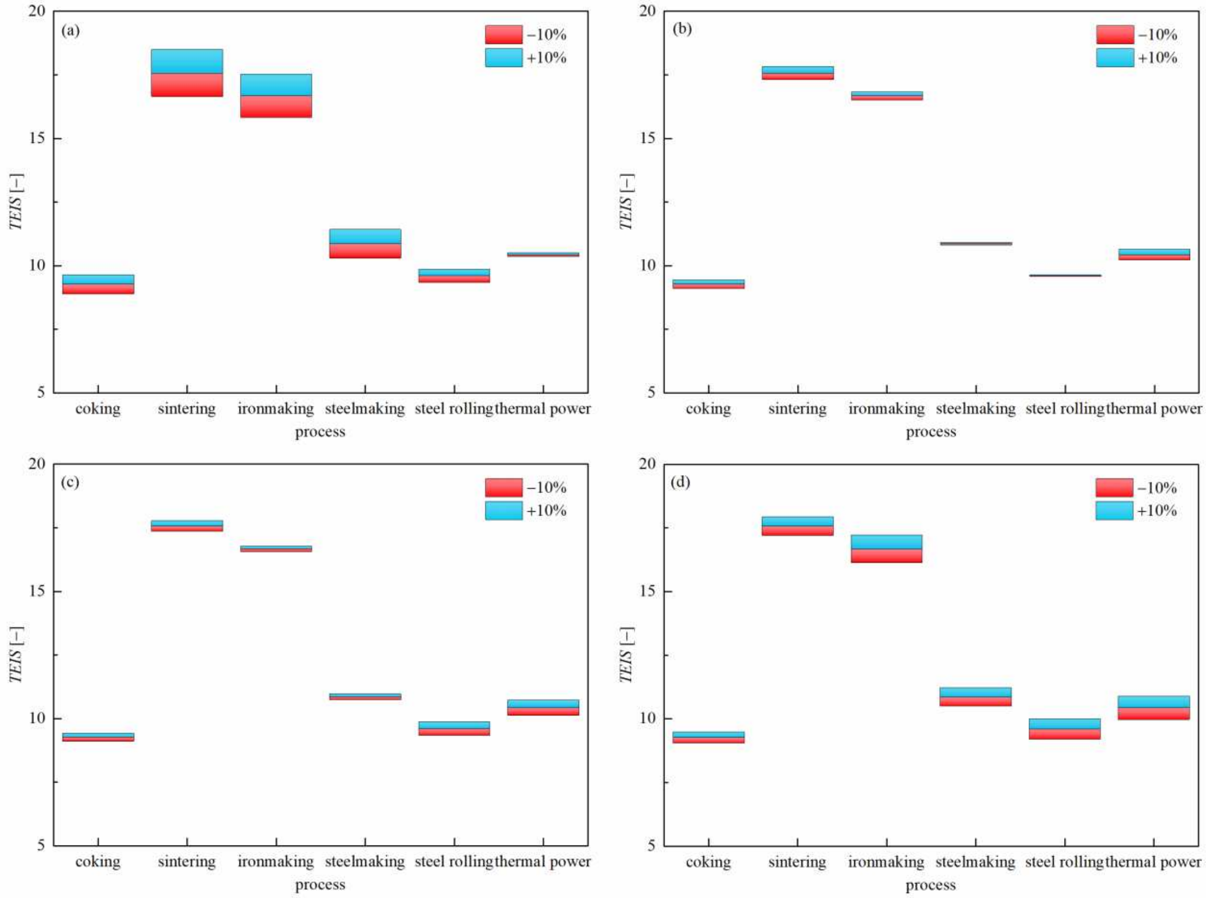

Fig. 9 Sensitivity analysis of weights. (a) PM; (b) SO_2; (c) NO_x; and (d) CO_2.

6 Conclusions

To assess the environmental impact of multi-air emissions of an industrial process more fairly and comprehensively, a TEIS index is defined in this work by simultaneously considering the emission concentration of each air emission substance, the flow rate of waste gases, and the availability of the emitting sources. The PM, SO_2, NO_x and CO_2 emitted from an integrated iron and steel site of China was selected as a case study to validate the feasibility and robustness of the TEIS approach. The main results are summarized as follows.

(1) A field measurement was conducted to obtain the synchronous data of waste gas flow rate and the concentration of PM, SO_2, NO_x and CO_2 from 22 main emitting sources of the iron and steel site. The highest PM, SO_2, NO_x and CO_2 emission concentrations are 38.12 mg/m^3, 138.26 mg/m^3, 217.28 mg/m^3, and 25.94%, respectively, occurring at CPG, SSM,

COS and COS.

(2) The environmental impacts of all processes of the site were assessed. The TEISs of the processes in descending order are listed as sintering, ironmaking, steelmaking, thermal power, steel rolling, and coking, with the values of 17.57, 16.68, 10.86, 10.43, 9.60 and 9.27, respectively. The comparison shows that the proposed TEIS approach is more feasible than the average-based method. Also, the effects of availability and flow rate on the TEIS are non-negligible.

(3) The sensitivity analysis indicates that the TEIS is not sensitive to the permissible CO_2 concentration limit and the weight of each air emission substance. With the change of 10% in each parameter, the TEIS sequence is basically the same with only minor sequential variation when the weight of PM changes.

Conflicts of interest

There are no conflicts to declare.

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